Studies of the Spin Dynamics of Charge Carriers in Semiconductors and their Interfaces

S. K. Singh, T. V. Shahbazyan, I. E. Perakis and N. H. Tolk

Department of Physics and Astronomy
Vanderbilt University, Nashville, TN 37235

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Objectives

✹ Measure Important Parameters in Magnetic Semiconductors:

◆ Band-Offset: Using Internal Photo-Emission (IPE) and SHG Techniques.

◆ Ultrafast Spin Dynamics: Time-Resolved Photoluminescence and Reflectivity, Faraday Rotation.

◆ Probing Electron-Hole Dynamics: Time-Dependent Second Harmonic Generation (SHG).

✹ Develop Theoretical Models of Ultrafast Spin Dynamics.
Vanderbilt Capabilities

◆ Series of Ultrafast, High-Power, Tunable Lasers:

  FIR and UV OPAs (Optical Parameteric Amplifier)
  Range: 0.06 – 6 eV  Pulse Energy: 10 \(\mu\)J
  Rep. Rate: 1 KHz  Pulse Width: 150 fs or 3.5 ps

  Free Electron Laser
  Range: 0.1 – 1 eV  Pulse Energy: \(~ 50\) mJ
  Rep. Rate: 30 Hz  Pulse Width: 4 - 6 \(\mu\)s

  Several Ti:Sapphire and Other Lasers

◆ 9 T Superconducting Magnet Having Four Optical Windows.

◆ Fast Electronics, Optics, etc.
**Band-Offset Measurements in Si/Si$_{0.45}$Ge$_{0.5}$**

• IPE is a sensitive technique to measure band offset (within 10 meV).

⇒ Can be used to measure band offsets in Magnetic Semiconductors (e.g. InMnAs/GaMnSb)
Proposed Band-Offset Measurements in $\text{III}_{1-x}\text{Mn}_x\text{V} / \text{III-V}$ based Semiconductor

- Band offsets can be measured as a function of Magnetic field.
Proposed Lifetime Measurements of Spin-Polarized Carriers in Magnetic Semiconductors (e.g. In$_{1-x}$Mn$_x$As/GaSb)

- Create Photo-Excited Spin-Polarized Carriers in InAs Quantum Well.
- Probe Spin-Scattering Mechanisms: Time-Resolved Photoluminescence in Magnetic Field.
- Faraday Rotation
- Study Role of Mn ion in Spin Scattering
Theory: Electric-Field-Induced-SH (EFISH)

General Equation for SHG:

\[ P(2\omega) = \chi^{(2)}_{d,B} E(\omega)E(\omega) + \chi^{(2)}_{d,S} E(\omega)E(\omega) + \chi^{(2)}_{q,B} E(\omega)\nabla E(\omega) + \chi^{(3)}_{d,B} \varepsilon(\omega \sim 0) E(\omega)E(\omega) \]

- \( \chi^{(3)}_{d,B} \varepsilon(\omega \sim 0) E(\omega)E(\omega) \): Electric–Field–Induced SH
- \( \varepsilon(\omega \sim 0) \): Space Charge Field at the Interface
- \( E(\omega) \): Electric Field of Fundamental Beam
System With Inversion Symmetry

Under Electric Dipole Approximation

\[ P(2\omega) = \chi^{(2)} E(\omega) E(\omega) \]

\[ -P(2\omega) = \chi^{(2)} (-E(\omega))(-E(\omega)) \]

\[ \chi^{(2)} = 0 \text{ in Bulk} \]

But not at surfaces or with static electric field where symmetry is broken
Experimental Setup

Ti: Sapphire Laser
\( \lambda = 700-920 \text{ nm}, \)  
\( \tau_p = 100 \text{ fs}, \)  
\( P_{\text{av}} = 400 \text{ mW} \)

\[ I^{(2\omega)}(t) \propto \left| \chi^{(2)} + \chi^{(3)} E(t) \right|^2 I^{(\omega)^2} \]
Electron-Hole Dynamics at Si/SiO$_2$ Interface

**Diagram:**
- \( E_{DC} \) Field \( \Rightarrow \) Charge Separation (Carrier Injection)
  - Electrons trapped at Surface
  - New Charged Traps in Oxide due to Radiation

**Graph:**
- SHG Signal (Counts/100 mSec) vs Time (Sec)
- Laser Blocked
Comparison of SiO$_2$ and ZrSiO$_x$ Oxides

- Qualitative difference in the shape of the curves in SiO$_2$ and ZrSiO$_x$:

\[ \Rightarrow \text{Difference in electron and hole injection rate?} \]
SHG measurements to probe electron-hole Dynamics in Magnetic Semiconductor

**SHG measurements can probe dynamic electric field due to electron-hole migration, induced by photons.**

*⇒ Understand photo-induced Ferromagnetism.*

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**EFL**

- **Electrons**
- **Holes**
- **CB**
- **VB**
- **EF**
- **In$_{1-x}$Mn$_x$As**
- **GaSb**
- **GaAs (100)**

**Material Stack**

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>In$<em>{0.94}$Mn$</em>{0.06}$As</td>
<td>12 nm</td>
</tr>
<tr>
<td>GaSb</td>
<td>500 nm</td>
</tr>
<tr>
<td>GaAs</td>
<td>300 nm</td>
</tr>
</tbody>
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Koshihara *et al.*, PRL 78, 4617 (1997)
Summary

- **Band-Offset**: Internal Photo-Emission (IPE) and SHG Techniques.
- **Lifetime of Photo-Excited Spin-Polarized Carriers**: Faraday Rotation, Time-Resolved Photoluminescence and Reflectivity.
- **Probing Electron-Hole Dynamics**: Time-Dependent Second Harmonic Generation (SHG).
- **Develop Theoretical Models** of Ultrafast Spin Dynamics.
Samples

- InAs/GaMnSb, InMnAs/GaMnSb : BO
- InAs/GaSb : BO, SHG
- InMnAs/GaSb : SHG
- GaSb/InMnAs/GaSb QW : LT

BO: Band Offset
LT: Life Time
SHG: Second Harmonic Generation